Observation of the cooling of free sodium atoms in a resonance laser field with a scanning frequency

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The cooling of Na atoms in the atomic beam was accomplished by using a continuous laser with a scanning radiation frequency and optical pumping of atoms.

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In this paper, we give the results of the first experiments on observation of radiation cooling of sodium atoms in a resonance laser field. This experiment was inspired by the work of Hänsch and Schawlow[1] and Letokhov *et al.*[2] Hänsch and Schawlow[1] proposed the idea of radiation cooling of atoms by multiple absorption of directed photons and their isotron emission, and Letokhov *et al.*[2] proposed a method and calculated adiabatic cooling of the atoms in a resonance laser field with a scanning frequency.

Neuhauser *et al.*[3] and Wineland *et al.*[4] demonstrated the cooling of Ba^+ and M^+ ions by laser radiation, which are initially localized in electromagnetic traps.

Radiation cooling of atoms can be achieved by irradiating the atom by an incident resonance light wave. The two-level atom, which is in resonance with the laser radiation, can be acted upon by the spontaneous light pressure given by

$$F_{sp} = \frac{1}{2}\left(\frac{\hbar k}{\tau}\right)\left(1 + \frac{1}{f}\right)^{-1}, \qquad (1)$$

where $\hbar k$ is the angular momentum of the photon, τ is the lifetime of the excited state, and f is the ratio of the average population of the excited and ground states (for a highly saturated transition $f = 1$). The atom is slowed down by the action of the spontaneous light pressure of the incident wave and its absorption frequency goes out of resonance with the laser field. If the later radiation frequency is continuously tuned to the resonance frequency of the slowed-down atom, then the atom can be thoroughly cooled.[2] Such cooling mode is called adiabatic.

The idea behind the experiment consists of observing the resonance fluorescence contour of a sodium atom in an incident laser wave with a scanning frequency. When the scanning rate of the laser radiation frequency is close to that of the cooling of the atom, the fraction of fast atoms should decrease and the fraction of slow atoms should increase, i.e., a noticeable deformation of the florescence line contour due to the frequency scanning should be observed. In a different scanning mode (too fast or too slow) such a distortion of the profile should not occur.

When the scanning is very fast the rate of variation of the laser frequency exceeds that of the absorption frequency of the atom because of the decrease in the velocity of its motion and the laser radiation frequency goes out of resonance with the absorption frequency of the atom. At slow scanning mode the frequency of the atomic transition is in resonance with the laser radiation frequency, but in this scanning mode the path length of the interaction increases and only the slow atoms are cooled, since the interaction path length is limited in the experiment.

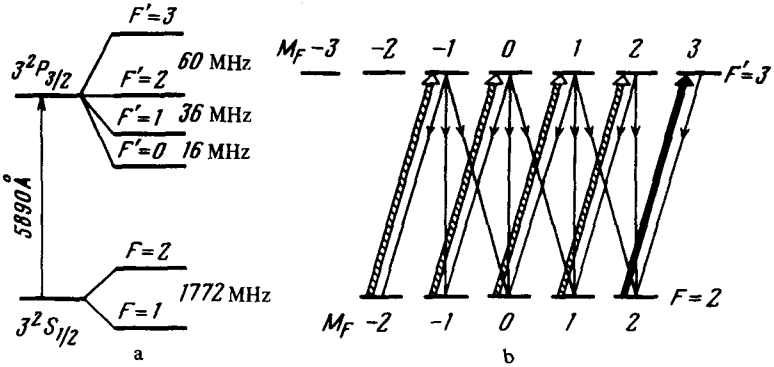

FIG. 1. a, The energy diagram of the hyperfine structure of the sodium atom line; b, optical orientation of the Na atom by means of a circularly polarized laser beam (σ^+).

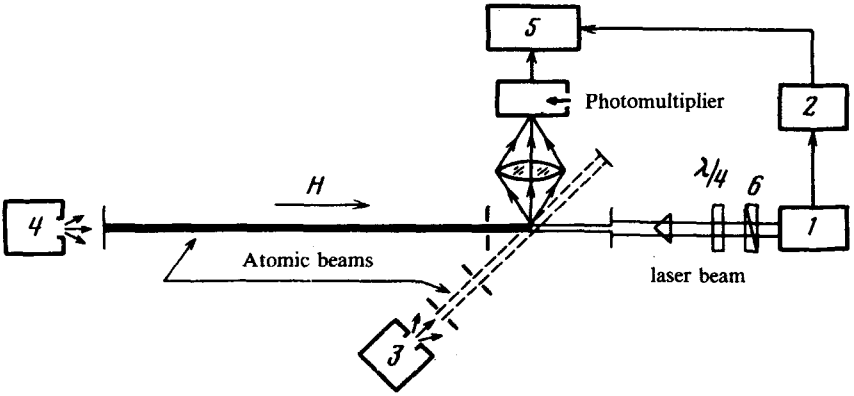

FIG. 2. The experimental setup: 1, Continuous dye laser; 2, frequency-control unit for the laser; 3 and 4, atomic-beam furnaces; 5, C1-70 oscillograph; 6, Glan prism.

In spite of the simplicity of this idea, it is difficult to realize it experimentally, since a multiple (10^3–10^5 fold) cyclic excitation with the laser field of the same atom, which has a hyperfine level splitting (Fig. 1a) would have to be produced. We were able to overcome this difficulty by a preliminary optical orientation of the atom in a circularly polarized σ^+ laser radiation.

To do this, we tuned the circularly polarized laser radiation in resonance with the transition of the atom $^2S_{1/2}$, $F=2 \rightarrow {}^2P_{3/2}$, $F'=3$ (Fig. 1b). The intensive laser radiation excites the transitions and changes the magnetic quantum number $\Delta m = 1$. As a result of these and the spontaneous transitions, the atom appears in the sublevel $F=2$, $m_F=2$. When the laser exceeds the saturation power ($P=10$ mW/cm^2), the time required for optical orientation is equal to 2 μsec, which is a small fraction of the total time of interaction of the atom with the radiation needed for the cooling (1 msec).

The transitions $F=2$ $(m_F=2) - F'=2 (m'_F = -2, -1, 0, 1, 2)$ in this case are forbidden because of the selection rules. Thus, the atom on sub-level F^2, $m_F=2$, will interact cyclically with a circularly polarized laser radiation.

The experimental setup, shown in Fig. 2, consists of the following principal elements: a continuous dye laser (1) (model 580A built by "Spectra-Physics"), cells with sources of main (2) and reference (3) atomic beams, and a system for recording the fluorescence signal from the atoms [photomultiplier FEU-79 and C1-70 oscillograph]. The scanning rate of the laser radiation frequency was periodically changed. The maximum scanning rate was equal to 370 MHz/msec. The cell in which the interaction of radiation with the atoms occurred was evacuated to a pressure of 5×10^{-6} Torr. The main beam (4) was collimated by two diaphragms $d_1=1.2$ mm and $d_2=2$ mm–spaced 30 cm apart. The region of intersection of the two atomic beams and the laser radiation were displayed on the cathode of the photomultiplier. The fluorescence signal could be either recorded from the atoms of the main beam or from the atoms of the reference beam (3) or from both beams together.

The main atomic beam was collinear to the laser radiation and the reference

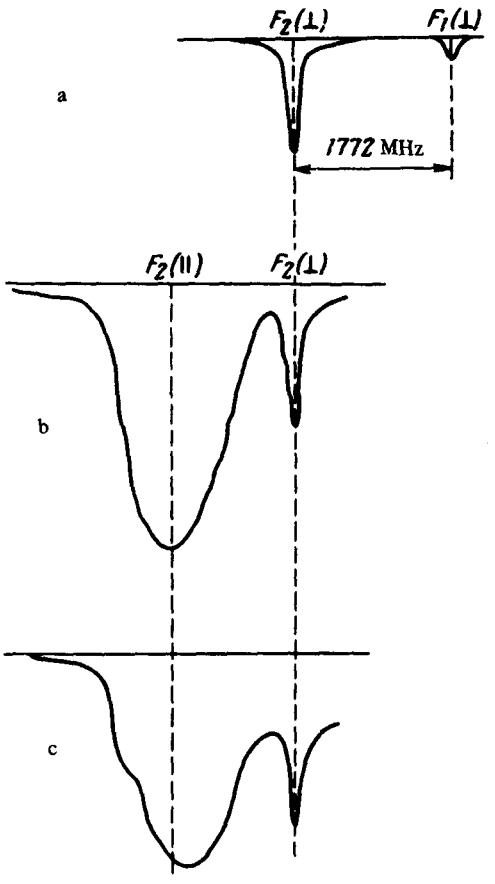

FIG. 3. Atomic-absorption lines in the parallel and perpendicular atomic beams: a, absorption line in the perpendicular beams; b, absorption line in the parallel and perpendicular atomic beams. Scanning rate - 46 MHz/msec, c, scanning rates -370 MHz/msec. Intensity of the laser beam -50 mW/cm^2.

atomic beam was perpendicular to the laser beam. The 37-cm interaction length of the main atomic beam with the laser radiation was equal to the calculated path length of the atom with an average velocity during its adiabatic interaction with the laser radiation prior to its cooling.

Figure 3 shows the results of observation of the absorption line of the atoms of the main and reference beams as a result of scanning of the laser frequency. The distance between the components of the hyperfine structure was 1772 MHz and the Doppler broadening in the longitudinal atomic beam at the furnace temperature of 300 °C was 1340 MHz.

Figure 3(a) shows the absorption line of the atoms in the perpendicular beam, which is used for calibration of the frequency scale. The two absorption peaks correspond to hyperfine splitting of the ground state of the Na atoms. The location of the $F_2(\perp)$ peak on the frequency scale corresponds to the absorption frequency of the atoms from the parallel beam with a zero velocity.

Figure 3(b) shows the absorption lines of the atoms in the parallel and perpendicular beams for a slow (46 MHz/msec) scanning rate of the laser radiation frequen-

cy, i.e., in the mode far from adiabatic. At such scanning rate the resonance interaction of the laser radiation cannot influence the motion of the atoms and the curves represent a common absorption line of atoms in both beams.

Figure 3(c) shows the absorption lines of the atoms in both beams at a scanning rate (370 MHz/msec) which is close, according to our estimates, to the adiabatic intersection of atoms with a velocity $v \leqslant 0.5\, v_0$, where v_0 is the most probable velocity of the atoms. The deformation of the absorption line is clearly noticeable in the parallel beam when the scanning rate of the frequency is increased. We notice that: 1) a shift occurs in the peak of the absorption line toward the frequency region corresponding to slower atoms and 2) the fluorescence signal increases at frequencies corresponding to the slow atoms. We attribute such a deformation of the absorption line to a velocity redistribution of the atoms toward the region of slower velocities, i.e., their slowing-down. The deformation of the absorption line is attributed primarily to the slowing-down of the atoms with velocities that are lower than the average velocity of the atoms in the beam. This is explained by the fact that the maximum scanning rate obtained in the experiment was too low to noticeably slow down the atoms with velocities greater than v_0. During scanning these atoms shift only slightly toward the region of lower velocities.

Our first observations of adiabatic cooling of free atoms in the resonance laser field showed that a direct control of the rate of motion of the atoms by laser radiation is possible. The next step involves deep adiabatic cooling of the atoms with any velocities from the thermal distribution, by scanning of the laser frequency up to the neighborhood of the center of the line, and subsequent stabilization at the frequency $(\omega_0 - \Gamma)$, where Γ is the radiation width of the line.[2] At this mode of controlled frequency scanning the atoms can be cooled to much lower temperatures.

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